International Journal of Advance and Innovative Research
Volume 13, Issue 1 (IV): January - March 2026
ISSN 2394 - 7780

JVM's Mehta Degree College, Sector 19, Airoli
NAAC Re-accredited "A+" Grade
IQAC in association with Western Regional Centre, ICSSR Organized one day National Conference on "Integrating Multidisciplinary Approaches to Build a Resilient and Sustainable Future", held on 10th January 2026

FIRE EXTINGUISHER DEVELOPMENT WITH A FOCUS ON SUSTAINABILITY: A REVIEW

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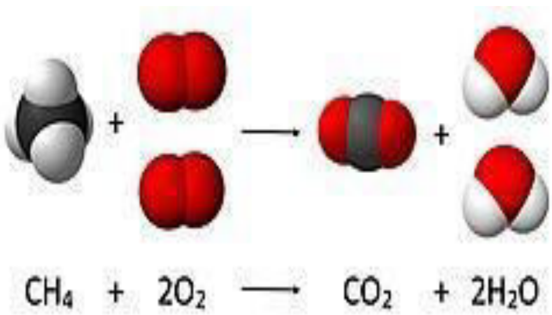
ABSTRACT
This article seeks to enhance the development of environmentally friendly fire extinguishers for sustainable applications. In recent years, the air quality in major cities has adversely affected human health, impacting lung capacity, causing skin irritation, leading to eye diseases, and more. Therefore, to reduce the reliance on traditional extinguishing agents, it is essential to consider green fire extinguishing agents that are non-toxic and environmentally safe. Currently, hydrogel stands out as one of the most significant extinguishing agents. This natural polymer hydrogel, characterized by its high-water retention, excellent film-forming capabilities, superior heat insulation, eco-friendliness, and biodegradability, holds immense potential for achieving breakthroughs in the development of clean and efficient fire extinguishing materials and products. Hydrogel is free from any PFAS (Polyfluoroalkyl Substances) and has a carbon footprint of less than 0.7%. This review elucidates the principles of extinguishing agents and discusses preparation strategies and high performance. In addition to hydrogel, HM powder (hydromagnesite), a carbonate mineral, is also recognized for its high performance as a fire extinguishing agent. Looking ahead, hydrogel extinguishing agents show great promise but require further research and development to address existing challenges.

In addition to hydrogel, a novel aqueous fire-extinguishing agent (AFEA) has been developed, which is a 40% aqueous solution of $CuCl_2$. The AFEA was created by dissolving copper (II) chloride dihydrate in water, noted for its exceptional efficacy as a fire extinguishing agent.

From a future standpoint, hydrogel extinguishing agents show great potential; however, further research and development are necessary to address existing challenges.

Keywords: *Fire extinguishants, hydrogel, carbon footprint, Hydromagnesite, PFAS, AFEA*

INTRODUCTION
Fire is a chemical reaction where a fuel interacts with an oxidizing agent, producing carbon dioxide and water. This reaction, referred to as combustion, does not occur in a straightforward manner and includes intermediates [1]. While oxygen is the most common oxidizing agent, other substances can also serve this function. For example, chlorine trifluoride can ignite sand.



Fire incidents are inherently unpredictable, particularly oil fires, which frequently result in significant losses due to their resistance to rapid extinguishment. Incidents are inevitable, despite the fact that it is preferable to avert them through robust preventive strategies.

Once ignited, a chain reaction must occur in which fires can maintain their own heat through the additional release of heat energy during combustion, and may spread, as long as there is a continuous supply of both an oxidizer and fuel[2]. If the oxidizer is oxygen from the ambient air, a force of gravity,[3] or a similar force resulting from acceleration, is essential to create convection, which eliminates combustion byproducts and delivers a supply of oxygen to the fire. Without gravity, the products of combustion and non-reactive gases

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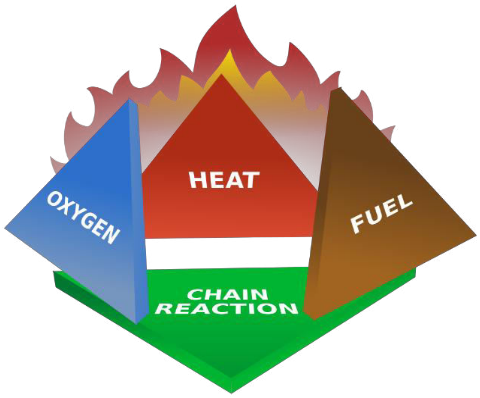
accumulate around the flame. This accumulation restricts the supply of oxygen to the reaction zone, ultimately causing the fire to self-extinguish.

Consequently, the risk of fire in a spacecraft is minimal when it is traveling in inertial flight.[4,5]. This does not hold true if oxygen is provided to the fire through a method other than thermal convection.



As we know that no fire is small. Fire can be extinguished by eliminating any one of the components of the fire tetrahedron. Take, for instance, a natural gas flame, such as that produced by a stove-top burner. The fire can be extinguished through any of the following methods: shutting off the gas supply, which eliminates the fuel source; completely covering the flame, which smothers it as the combustion process consumes the available oxidizer (the oxygen present in the air) and replaces it in the vicinity of the flame with CO_2; using an inert gas like carbon dioxide, which smothers the flame by displacing the available oxidizer; applying water, which extracts heat from the fire more rapidly than the fire can generate it (similarly, blowing forcefully on a flame will remove the heat from the currently burning gas away from its fuel source, achieving the same result); or utilizing a retardant chemical such as Halon (which has been largely prohibited in certain countries as of 2023) on the flame, which slows down the chemical reaction itself until the rate of combustion becomes too slow to sustain the chain reaction. Conversely, fire can be intensified by increasing the overall rate of combustion. Techniques to achieve this include adjusting the input of fuel and oxidizer to stoichiometric ratios enhancing the input of both fuel and oxidizer in this balanced mixture, raising the ambient temperature so that the fire's own heat can more effectively sustain combustion, or introducing a catalyst, a non-reactive medium that facilitates a more efficient reaction between the fuel and oxidizer.

Consequently, in the interest of environmental preservation and energy efficiency, the effectiveness of the water mist system for fire extinguishing, utilizing pure water and a low concentration of eco-friendly additives, is investigated. A comparison was made between the self-produced polymer composite additives and NaCl salt against the pure water mist system. The results indicate that within this low-pressure system, the 1% polymer composite additives exhibited the highest improvement in extinction efficiency, while pure water demonstrated greater effectiveness under medium and high pressure, and the 1% NaCl salt additive showed a negative correlation with extinction efficiency.

The effectiveness of water mist combined with potassium salt additives in suppressing liquid pool fires has been experimentally examined within a confined environment. The penetration pool fire ratio (PPFR) has been employed to assess the ability of water mist to penetrate directly above the source of a pool fire. The PPFR is determined through experimental measurements of the water mass during the corresponding extinguishing time when no fire is present, revealing a critical PPFR range of 40–45%. This indicates that for the additives to exert a chemical effect, more than 45% of the water mist droplets must reach the fuel surface. The suppression efficiency can generally be ranked in the following order: $KNO_3 \approx K_2C_2O_4 > K_3PO_4 \approx$ pure water. The chemical mechanism behind the potassium additives involves the formation of active substances KOH and KxOy at elevated temperatures, and the enhancement effect of CO produced by the thermal decomposition of $K_2C_2O_4$ in the confined volume is significantly greater than the fire source can be disregarded. All findings suggest that the inclusion of potassium salts enhances the extinguishing efficiency of water mist on liquid fires, with the suppression mechanism attributed to a combination of physical and chemical actions.

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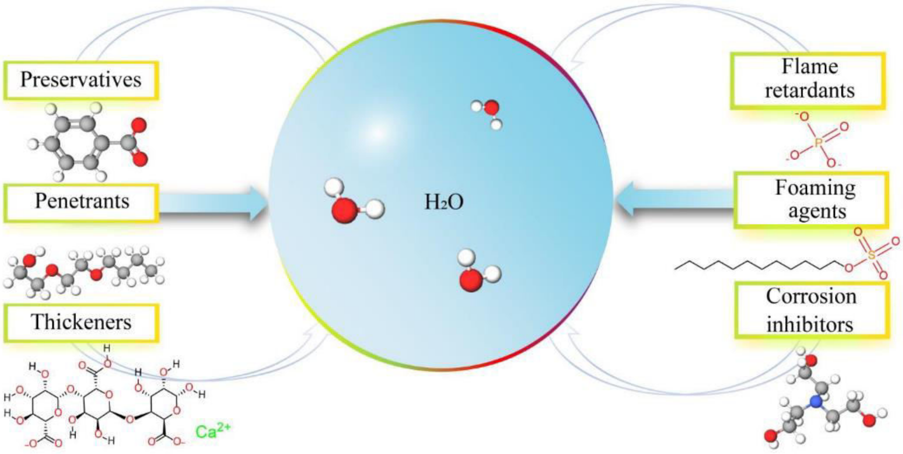

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LITERATURE REVIEW

Fire extinguishing technologies have undergone substantial development in response to growing concerns related to fire safety, environmental sustainability, and the limitations of conventional extinguishing agents. Traditional fire extinguishers such as water, foam, halons, and chemical powders are widely used but often suffer from drawbacks including toxic byproducts, ozone depletion potential, corrosive residues, and limited effectiveness against specific fire classes [6]. These limitations have motivated extensive research into advanced materials and environmentally benign fire suppression systems.

Among emerging technologies, hydrogel-based fire extinguishing agents have gained significant attention due to their superior cooling efficiency and ability to suppress re-ignition. Li et al. provided a comprehensive review of hydrogel extinguishants, discussing their working principles, synthesis strategies, performance evaluation methods, existing challenges, and future prospects [7]. Hydrogels possess high water-retention capacity, strong adhesion to burning surfaces, and prolonged cooling effects, which collectively enhance fire suppression efficiency. Further studies have demonstrated that polymeric and hybrid hydrogel systems effectively reduce flame spread and smoke generation, making them promising candidates for modern fire protection applications [8].

Dry powder fire extinguishers continue to be among the most widely deployed fire suppression systems due to their rapid flame knockdown capability and broad applicability. Wang et al. developed a modified dry powder extinguishing agent based on potassium bicarbonate and hydromagnesite ($KHCO_3$@HM) and demonstrated its superior fire suppression efficiency through combined microscopic characterization and macroscopic extinguishing tests [9]. The synergistic effects arising from thermal decomposition and endothermic reactions contributed to improved flame inhibition. Similar investigations have shown that mineral-based additives such as magnesium hydroxide and layered double hydroxides can further enhance the performance and stability of dry powder extinguishing agents [10].

In addition to extinguishing agents, flame-retardant materials for protective textiles play a critical role in fire safety, particularly in firefighting and industrial protective clothing. Cellulose-based fabrics are commonly used due to their comfort and biodegradability; however, their inherent flammability restricts their application. Zhang et al. addressed this issue by developing phosphorus–nitrogen-containing branched compounds based on branched polyethyleneimine and dimethyl phosphite, which were crosslinked onto cotton fabrics using 1,2,3,4-butanetetracarboxylic acid [11]. The treated fabrics exhibited high limiting oxygen index values and maintained flame-retardant performance even after repeated laundering cycles. Previous studies have also highlighted the effectiveness of phosphorus–nitrogen synergistic systems in promoting char formation and suppressing flame propagation in cellulose-based materials [12].

Sustainable approaches to producing flame-retardant cellulose fabrics have further advanced through the use of green solvents and recyclable processing systems. The application of recyclable ternary deep eutectic solvents for fabricating surface ammonium phosphate-modified cellulose fabrics has been shown to significantly improve long-term flame retardancy [13]. These fabrics exhibited high limiting oxygen index values and retained their fire-resistant properties after extensive washing. Additionally, deep eutectic solvents are recognized for their low toxicity, reusability, and reduced environmental impact, making them suitable for sustainable textile processing [14].

Beyond textiles and powders, recent research has explored multifunctional fire extinguishing systems capable of combining fire suppression, smoke reduction, and environmental safety. Water-based composite extinguishants incorporating gels, inorganic salts, or nanoparticles have demonstrated improved fire suppression efficiency and reduced secondary pollution compared to conventional agents [15]. These developments reflect the growing emphasis on integrated and sustainable fire protection solutions.

Overall, the literature indicates a clear shift toward innovative, sustainable, and multifunctional fire extinguishing technologies. Advances in hydrogel extinguishants, enhanced dry powder formulations, flame-retardant cellulose textiles, and green solvent-based processing strategies collectively contribute to improved fire suppression efficiency, firefighter safety, and environmental sustainability. These studies provide a robust foundation for future research aimed at developing next-generation fire extinguishers.

METHODOLOGY

The methodology of this study is based on integrating **green chemistry, material engineering, and fire-safety testing** to develop sustainable fire extinguishing and flame-retardant systems. Emphasis is placed on one-step or low-energy synthesis routes, renewable raw materials, recyclable solvents, and multifunctional fire-protection platforms. The methodological approach combines material synthesis, encapsulation, structural modification, and standardized fire-performance evaluation.

1. One-Step Green Modification of Cellulose-Based Flame-Retardant Systems

A sustainable one-step surface modification strategy was adopted to prepare durable flame-retardant cellulose fabrics using a **recyclable ternary deep eutectic solvent (TDES)** system. Cellulose fabrics were treated in the TDES medium containing ammonium phosphate precursors, enabling phosphorylation of cellulose through hydrogen bonding and esterification without the use of toxic catalysts or organic solvents. The modified fabrics were washed and dried, and the solvent system was recovered for reuse to evaluate recyclability and process efficiency.

The flame-retardant performance was assessed through limiting oxygen index (LOI) measurements and laundering durability tests. Additional functional evaluations, including antibacterial activity and dye compatibility, were conducted to confirm suitability for firefighting and protective clothing applications. This approach minimizes chemical consumption while imparting long-lasting flame resistance and multifunctionality to cellulose substrates [16].

2. Preparation of Core–Shell Fire-Extinguishing Microcapsules

Fire-extinguishing microcapsules were fabricated using a **one-pot oil-in-oil/water emulsion method**. In this process, liquid fire-suppressant agents such as fluoroketones or hydrofluorocarbons were dissolved together with polymeric shell materials in a volatile solvent to form a composite solution. This solution was emulsified into polar and non-polar continuous phases by regulating surfactant concentration and mechanical agitation to achieve interfacial tension control.

Subsequent evaporation of the volatile solvent resulted in the formation of core–shell microcapsules encapsulating the extinguishing agent. The microcapsules were isolated and incorporated into polymer matrices to evaluate dispersion stability and controlled release behavior. Morphological and thermal analyses were performed to confirm encapsulation efficiency and fire-suppression capability [17].

3. Aerogel-Based Materials for Fire Protection

Aerogels were synthesized via sol–gel processing followed by controlled drying to obtain highly porous, ultra-lightweight structures with air-filled nanopores. The inherent porosity of aerogels significantly reduces heat transfer, making them effective thermal insulators. The prepared aerogels were evaluated for thermal stability, heat flux resistance, and flame retardancy.

Due to their low thermal conductivity and high temperature resistance, aerogels were assessed as passive fire-protection and insulation materials. Their potential application in fire barriers and thermal shields was analyzed based on standardized thermal and combustion testing protocols [18].

4. Bio-Based Flame Retardants for Polymeric Fire-Safe Materials

A green and water-based synthesis route was employed to prepare a bio-derived flame retardant through the reaction of **phytic acid and furfurylamine** under mild conditions. The resulting phosphorus–nitrogen-rich compound was incorporated into poly(lactic acid) (PLA) via melt blending at low loading levels.

Fire-retardant efficiency was evaluated using UL-94 vertical burning tests, limiting oxygen index measurements, and cone calorimetry. Mechanical and thermal properties of the composites were analyzed to ensure that flame resistance was achieved without compromising structural performance. The flame-retardant mechanism was investigated through char residue and thermal degradation analysis, indicating combined gas-phase and condensed-phase activity [19].

5. Development of Inherent Flame-Retardant Polyurethane Foams

An environmentally benign post-modification technique was used to prepare inherent flame-retardant polyurethane foams using **β-cyclodextrin (β-CD)** as both a chain extender and reactive flame-retardant component. β-CD, a bio-derived oligosaccharide, was incorporated into the polyurethane network, followed by esterification with phosphoric acid to introduce phosphorus-containing flame-retardant groups.

The modified foams were evaluated for limiting oxygen index, time to ignition, and total heat release using cone calorimeter testing. Mechanical properties such as compressive strength and resilience were also measured. The synergistic flame-retardant effect was attributed to enhanced char formation and crosslinked carbonaceous layers formed during combustion [20].

6. Fire-Performance Testing and Sustainability Assessment

All developed materials were systematically evaluated using standardized fire-testing methods, including LOI, UL-94, thermogravimetric analysis, and cone calorimetry. Sustainability metrics such as solvent recyclability, bio-based content, reduction in toxic additives, and durability were assessed to determine environmental impact. This methodology supports the development of scalable, eco-friendly fire extinguishing and flame-retardant technologies suitable for industrial and safety applications.

APPLICATIONS

Many of the polymers we utilize on a daily basis are extremely flammable. In the past, a significant number of residential fires were attributed to ignited polymeric substances until regulations were enacted mandating the inclusion of fire retardants in these materials. Fire retardants extend the duration before materials ignite, offering crucial time to avert a fire or to escape. Nevertheless, it has become evident that numerous conventional treatments employed as fire retardants pose risks to human health and are highly persistent in the environment. As the presence of polymeric materials in our homes and lives continues to grow, the ability to produce fire retardants remains essential; however, it is imperative to consider their environmental impact and sustainability. Green Fire Retardants for Polymeric Materials examines both the selection of various materials and treatments aimed at enhancing the fire resistance of polymeric substances, as well as eco-friendly methods for synthesizing these fire retardants. This resource is timely for green chemists seeking practical applications for their research and for polymer scientists eager to enhance the sustainability of their products and processes.

CHALLENGES FOR FIRE EXTINGUISHERS

Fire extinguishers play a crucial role in early-stage fire suppression; however, their effectiveness is limited by several technical, environmental, and operational challenges. One major limitation is **fire-class dependency**, as most extinguishers are designed to combat specific types of fires. Improper selection or misuse may reduce extinguishing efficiency or worsen fire conditions, especially in mixed-fuel environments [21].

Another significant challenge relates to the **environmental impact of extinguishing agents**. Conventional agents such as halons and fluorinated foams have been associated with ozone depletion and high global warming potential (GWP). Although halons have been phased out under international agreements, many replacement agents still pose environmental concerns due to their persistence and greenhouse effects [22,23].

Health and safety risks are also a critical concern. Dry chemical powders and gaseous agents can cause respiratory irritation, skin sensitization, and reduced visibility during discharge. In enclosed spaces, gaseous extinguishing systems may lead to oxygen depletion, posing risks to occupants and emergency responders [24].

Residue formation and post-fire damage further limit the applicability of several extinguishing agents. Dry powders and foam residues may corrode metals, damage electronic equipment, and require extensive cleanup, resulting in increased economic losses even after successful fire suppression [25].

The **storage stability and maintenance requirements** of fire extinguishers present additional challenges. Factors such as pressure loss, moisture absorption, chemical degradation, and caking of powders can significantly reduce extinguisher performance over time, particularly under adverse environmental conditions [26].

Emerging fire risks, including **lithium-ion battery fires and high-energy fuel systems**, expose the limitations of conventional extinguishers. Many traditional agents fail to provide sufficient cooling, leading to thermal runaway and re-ignition, thereby necessitating the development of advanced extinguishing materials with enhanced cooling and heat absorption capabilities [27].

Finally, **economic and regulatory constraints** hinder the large-scale adoption of innovative and eco-friendly extinguishing technologies. High production costs, lack of standardized testing protocols, and lengthy certification processes pose significant barriers to commercialization and widespread implementation [28].

CONCLUSION

This review critically examined the classification, mechanisms, and material advancements of fire extinguishers used for different fire scenarios. Conventional extinguishing agents continue to play a vital role in fire suppression; however, their environmental impact and safety limitations have driven the development of advanced and sustainable alternatives. Recent progress in eco-friendly formulations, including water-based gels, hydrogels, bio-derived compounds, and nanomaterial-assisted systems, has demonstrated improved thermal stability, flame inhibition, and suppression efficiency.

Despite these advancements, challenges related to cost-effectiveness, durability, large-scale production, and regulatory compliance persist. Addressing these issues requires continued research integrating fire science, materials engineering, and green chemistry principles. Overall, the reviewed studies highlight the importance of developing efficient, environmentally sustainable fire extinguisher technologies to meet evolving safety and environmental standards.

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